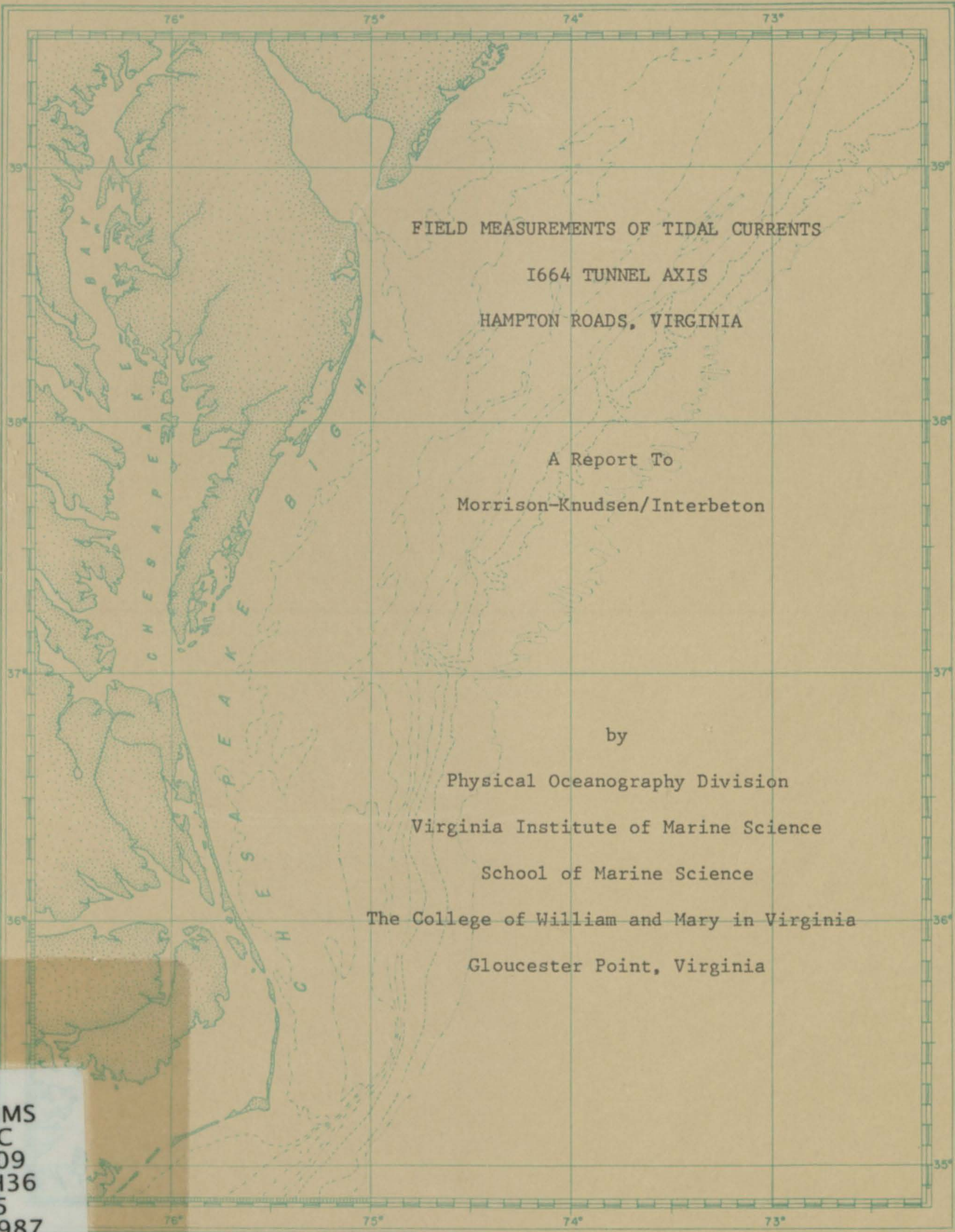
1987

Field measurements of tidal currents, I664 tunnel axis, Hampton Roads, Virginia : a report to Morrison-Knudsen/Interbeton

Physical Oceanography Division, Virginia Institute of Marine Science



FIELD MEASUREMENTS OF TIDAL CURRENTS

I664 TUNNEL AXIS

HAMPTON ROADS, VIRGINIA

A Report To

Morrison-Knudsen/Interbeton

by

Physical Oceanography Division

Virginia Institute of Marine Science

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TABLE OF CONTENTS

VOLUME ONE

EXECUTIVE SUMMARY

Currents in the region of Newport News Point of the James River were measured at the request of Morrison-Knudsen/Interbeton to examine maximum flood and ebb values during spring tides and determine first order relationships of current strengths and phase lags between this region and Chesapeake Bay Entrance predictions.

The study consisted of three field sampling periods:

A. 10 - 14 July 1987;
B. 27 July to 12 August 1987; and
C. 26 - 27 August 1987.

During the first sampling period, surface to bottom currents were measured at six locations along the proposed axis of the I664 tunnel extending south of Newport News Point, and near Navigation buoy #13 for one tidal cycle at each location. During period B, data was obtained at three levels at buoy #13 and in the final period, currents were measured at buoy #13 and between Newport News Point and the present Newport News Shipping Channel.

The two week time series of data at buoy #13 (approximately 0.3 nautical miles upstream of the proposed tunnel corridor) was used to establish phase lags of current features (slack water periods and maximum flood and ebb currents) as well as regression coefficients for current-current and current ratio relationships with Chesapeake Bay Entrance predictions and associated estimates of their standard errors.

Similar phase lag and current ratio information between Chesapeake Bay Entrance (CBE) predictions and currents measured along the tunnel corridor were also developed.

The study shows:

A. Ratios of measured currents (at buoy #13) to CBE predictions are a function of strength of the predicted current with smallest (neap tide) maximum flood and ebb currents having the greatest ratio.

B. The cyclic nature of flood and ebb currents most closely resembles a square wave or truncated saw tooth wave pattern rather than a sine wave.

C. True "slack water" was rarely encountered and minimum current speeds between flood and ebb were often greater than 10 cm/sec with cyclonic or anticyclonic rotation of currents during this time. Periods of minimum currents (less than 20 cm/sec) averaged 46 minutes for times prior to flooding and 56 minutes for times prior to ebbing for the buoy #13 location. Similar minimum current periods along the tunnel corridor ranged from 11 minutes to 1 hour (prior to flooding) and from 20 minutes to nearly 3 hours (prior to ebbing).

D. Duration of maximum flood currents (with speeds greater than 50 cm/sec) averaged 3 hours at buoy #13 and ranged from 1 to 3 hours along the tunnel corridor. For maximum ebb currents, these values were closer to 2 hr 40 minutes and 1 to 3 1/2 hours.

Difference between current strength predictions (from current ratios) and current phase lags obtained from this study and those found in tidal prediction tables for the west end of Newport News Shipping Channel are noted and, at least in part, attributed to obstructing tunnel islands which were constructed after the tide table values were developed but prior to the present study.

For convenience, this report has been segregated into two volumes. Volume One contains the written text with figures and tables pertinent to the text. Volume Two contains tables and plots of data collected.

PART A - JULY 10 - JULY 14 FIELD MEASUREMENTS

I. INTRODUCTION

The purpose of this project was to measure currents in the vicinity of the Interstate 664 (I664) tunnel which is being constructed from Newport News Point in the Hampton Roads section of the lower James River. Currents were to be measured at ten (10) foot depth intervals from near surface to the river bottom at seven (7) locations designated by the requester as shown in Figure 1. Station F, near James River Navigation Buoy #13, was to be a buoyed station and serve as a fixed reference station at which currents were to be measured for the duration of the study. Stations D_1, D_2 and D_3 (Figure 1) also were to be buoyed stations with currents to be measured for one complete tidal cycle on 11, 12 and 13 July respectively. Stations L_1, L_2 and L_3 were to be occupied using the research vessel Langley at anchor from which currents were to be measured during one complete tidal cycle on 11, 12 and 13 July respectively. Configurations of the F, D and L stations are shown in Figure 2. Concurrent with current measurements, water level variations (tidal height) were to be measured near Newport News Point.

II. METHODS AND TIMES OF CURRENT MEASUREMENTS

Two types of current meters were used: "S4's", an electromagnetic current meter manufactured by Interocean, and "Ruz meters", modified Braincon Histogram type meters which use a savonious rotor to measure current speed and vane oriented meter position to measure direction. Both types of instruments store data in solid state memory and are programmable with respect to frequency and duration of measurement. The S4 meters were programmed to sample north and east components of currents twice a second and store ten (10) second averages of these values. Modified Braincon current meters measured rotor revolutions for 32 seconds, instantaneous

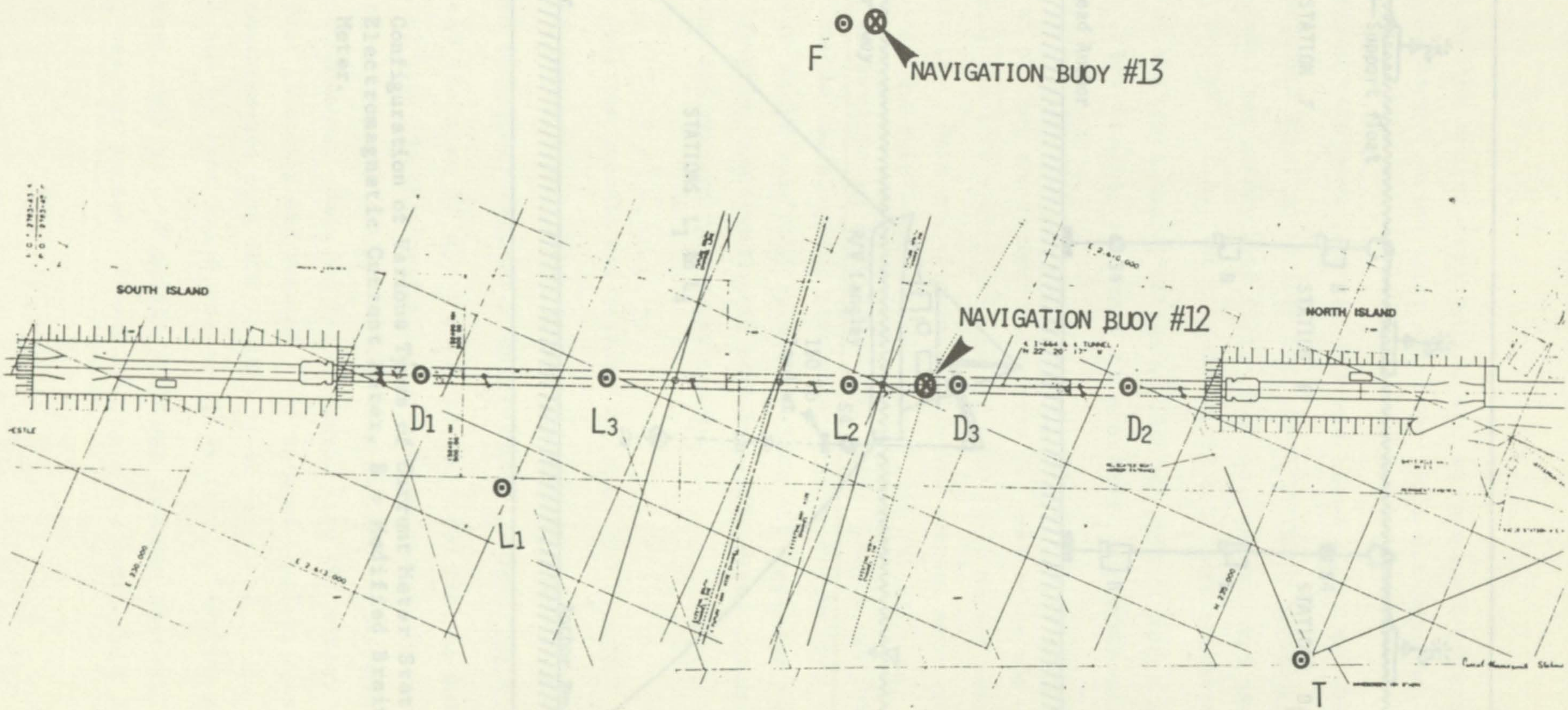

Figure 1. Proposed Stations for Measurement of Currents (F, D_1, D_2, D_3, L_1, L_2, L_3) and Tides (T) at the I664 Tunnel Corridor.

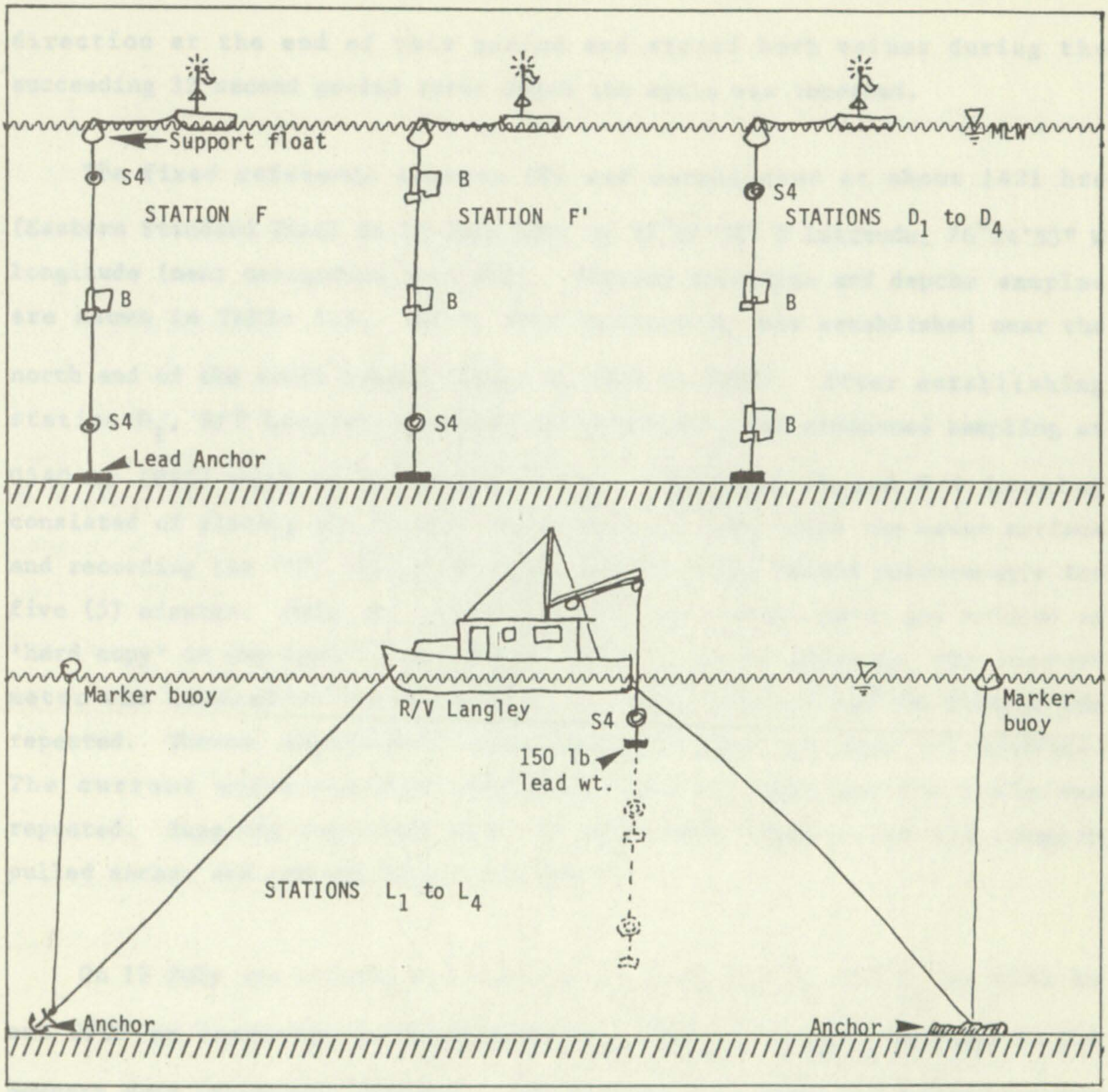

Figure 2. Configuration of Various Types of Current Meter Stations. S4 = Electromagnetic Current Meter, B = Modified Braincon Current Meter.

direction at the end of this period and stored both values during the succeeding 32 second period after which the cycle was repeated.

The fixed reference station (F) was established at about 1421 hrs (Eastern Standard Time) on 10 July 1987 at 37°57'02" N latitude, 76°24'53" W longitude (near navigation buoy #13). Station locations and depths sampled are shown in Table I.A. On 11 July Station D_1 was established near the north end of the south tunnel island at 0446 hr (EST). After establishing station D_1, R/V Langley anchored at station L_1 and commenced sampling at 0540 hr (EST) with an S4 current meter. Sampling aboard R/V Langley consisted of placing the current meter five (5) feet below the water surface and recording ten (10) second averages of half (1/2) second measurements for five (5) minutes. Data was recorded within the current meter and printed as 'hard copy' in the boat's laboratory. After five (5) minutes, the current meter was lowered to 15 feet below the water surface and the process was repeated. Thence, measurements were made at 25 feet for five (5) minutes. The current meter was then raised to five (5) feet and the cycle was repeated. Sampling continued until 1830 hrs (EST) after which R/V Langley pulled anchor and removed buoyed station D_1.

On 12 July the process was repeated at stations D_2 and L_2 at 0543 hr and 0707 hr respectively with station L_2 (the R/V Langley station) in the Newport News (shipping) Channel. At station L_2, sampling procedure was altered near the time of slack water before flood tide in order to obtain more detailed data (in the vertical) when a front passed the anchor station. Sampling procedure was changed by sampling for two (2) minutes at five (5) foot depth increments. Once the front passed, five (5) minute sampling at ten (10) foot intervals was resumed. The altered sampling consisted of one series of measurements form 1806 to 1823 hr at depths of 5, 10, 15, 20, 25, 30, 35, 40 and 45 feet below the water surface. Sampling at station L_2 ended at about 1945 hr. A squall line was passing through the area so station D_2 was not pulled. It was left in place until about 0500 hr on 13 July.

On 13 July station D_3 was set at 0625 hr and sampling from R/V Langley at station L_3 commenced at 0721 hr. Sampling at station L_3 continued until 2008 hr.

III. DIFFICULTIES

During the course of the field campaign, several difficulties arose resulting from environmental conditions, mechanical failure and human error. Strong currents and bottom substrate resulted in difficulty holding R/V Langley at anchor. On several occasions sampling was interrupted while anchors were re-set. At station L_1, no data was taken between 1256 and 1348 hrs when the cable between the current meter and deck readout became entangled in the boat's propellor and had to be replaced. Additionally, no data was taken during the six (6) minute period 1728-1734 while the anchor was reset. At station L_2 sampling stopped for eleven (11) minutes (1157-1208) and forty minutes (1230-1310) while anchors were reset. Similarly, at station L_3 no data was taken for 57 minutes (0859-0956) and 34 minutes (1157-1231) while anchors were reset.

Soon after station D_1 was set it was struck by a crew boat or tug with barge. When the uppermost current meter from this station (an S4) was being subjected to post-deployment calibration, it was found to contain water and its compass was locked.

A defective sensor on the current meter at 16 ft at station F resulted in loss of current speed information at this level. Additionally, a programming error in the current meters at the 6 and 26 foot levels at this station caused their memories to fill after 17 hours (1421 on 10 July to 0721, 11 July). A similar error resulted in only 2.5 hours of data collection from the 5 foot level at station D_2 (0459 to 0724 on 12 July). This station was re-occupied as station D_4 from 2249 hr on 13 July to 1224 hr on 14 July.

Finally, difficulties were encountered in establishing stations at the desired locations. In all cases, stations were placed within 100-meters of the desired locations. Final station positions are listed in Table I and shown in Figure 3.

IV. RESULTS

Currents - Current measurements are expressed as five (5) minute averages of speed and direction resulting from vector averages of either ten (10) second measurements with S4 current meters or 32 second measurements with the Ruz meters. Results are presented as listing in Tables II to VIII and as plots of speed and direction vs time in Figures 4 to 10. Stick plots of currents are also provided for the buoyed stations (F, D_1, D_2, D_3, and D_4). No stick plots are provided for the L stations because of unequal temporal spacing of data.

Tides - Tidal heights were measured at the jetty to the east of the Small Boat Harbor entrance. Hourly water levels relative to mean sea level are listed in Table IX and plotted in Figure 11. Times and values of minimum and maximum water levels are given in Table X.

TABLE I

Depths at which currents were measured

Date	Station	Location Latitude	Location Longitude	Depths (Feet)
A.	**10-14 July 1987**			
10-14 July	F	$36^{o}57'02"N$	$76^{o}24'53"W$	6, 16, 26 (below MLW)
11 July	D_1	$36^{o}56'55"N$	$76^{o}24'21"W$	5.0, 14.75, 22.0 "
12 July	D_2 *	$36^{o}57'29"N$	$76^{o}24"37'W$	5.0, 14.75, 19.0 "
13 July	D_3	$36^{o}57'21"N$	$76^{o}24'30"W$	5.0, 14.75, 19.2 "
13-14 July	D_4 *	$36^{o}57'29"N$	$76^{o}24'37"W$	5.0, 14.75, 19.0 "
11 July	L_1	$36^{o}57'01'N$	$76^{o}24'17"W$	5, 15, 25 (below SFC)
12 July	L_2	$36^{o}57'19"N$	$76^{o}24'35"W$	**5,15,25,35,45 "
13 July	L_3	$36^{o}57'04"N$	$76^{o}24'27"$	5, 15, 24 "
B.	**27 July-27 August 1987**			
27 Jul-12 Aug	F'	$36^{o}57'08"N$	$76^{o}24'57"W$	5, 15, 25 (below MLW)
26-27 Aug	F'	$36^{o}57'08"N$	$76^{o}24'57"W$	5, 15, 25 "
26-27 Aug	L_4	$36^{o}57'26"N$	$76^{o}24'37"W$	5,10,15,20 (below SFC)

*Station D_2 re-occupied as D_4 on 13-14 July

**Additional measurements at 10, 20, 30 & 40 ft one time

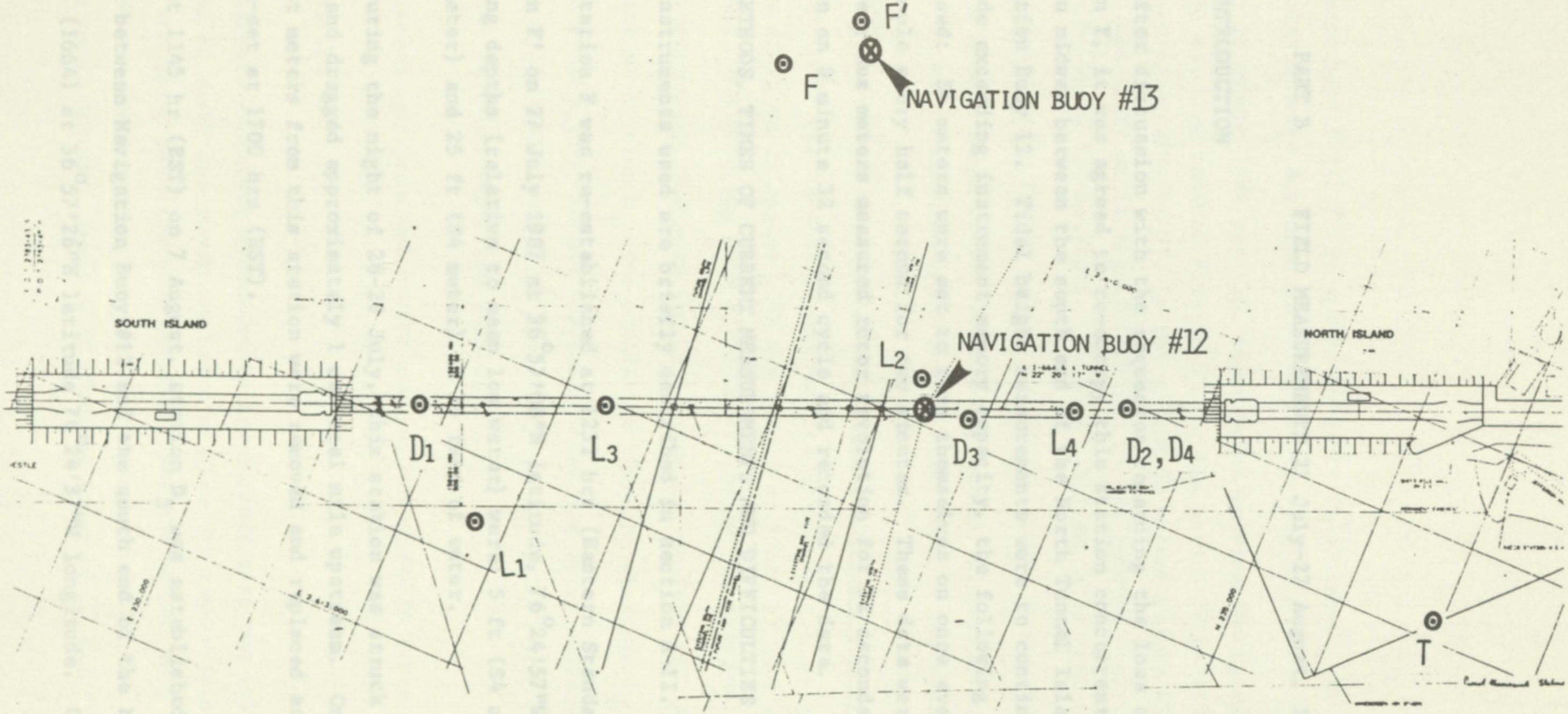

Figure 3. Locations where Currents (F, F', D_1, D_2, D_3, D_4, L_1, L_2, L_3, L_4) and Tides (T) were Measured at the I664 tunnel corridor. Stations F' and L_4 were occupied after 27 July 1987.

PART B FIELD MEASUREMENTS 27 July-27 August, 1987

I. INTRODUCTION

After discussion with the requestor regarding the loss of data at station F, it was agreed to re-occupy this station concurrently with a station midway between the south end of the North Tunnel Island and Navigation Buoy 12. Tidal height measurements were to continue also. To preclude exceeding instrument memory capacity, the following sampling rates were used: S4 meters were set to turn themselves on once every five minutes and sample every half second for two minutes. These data were averaged and recorded; Ruz meters measured rotor revolution for 32 seconds and direction once on an 8 minute 32 second cycle and recorded the data.

II. METHODS, TIMES OF CURRENT MEASUREMENTS AND DIFFICULTIES

Instruments used are briefly described in section A-II.

Station F was re-established at 1232 hrs (Eastern Standard Time) as Station F' on 27 July 1987 at 36°57'08"N latitude, 76°24'57"W longitude. Sampling depths (relative to mean low water) were: 5 ft (S4 meter), 15 ft (Ruz meter) and 25 ft (S4 meter) in 36 feet of water.

During the night of 28-29 July, this station was struck by a ship or barge and dragged approximately 1 nautical mile upstream. On 30 July, current meters from this station were removed and replaced and the station was re-set at 1700 hrs (EST).

At 1145 hr (EST) on 7 August, station D_5 was established approximately midway between Navigation Buoy #12 and the south end of the North Tunnel Island (I664) at 36°57'26"N latitude 76°24'37"W longitude. Current meters were located at 5 ft, 15 ft and 20 ft in 23 ft of water. All current meters at station D_5 were Ruz meters.

On 11 August 1987 the U.S. Coast Guard serviced Navigation Buoy #13. In doing so, they removed station F' for the period 0710-0936 hrs (EST). When they reset station F', it was placed in approximately 45 ft of water. At 0930 hrs (EST) on 12 August, station F' was removed. At this time, station D_5 could not be found. We were notified later that the surface marker from station D_5 had been found adrift on the south side of the James River by a work barge crew. Extensive searches for current meters from station D_5 were conducted on 12 and 14 August and 14 September. Meters were not found.

Station F' was re-established at its previous (27 July) location at 1235 hrs (EST) on 26 August with Ruz meters at 5 and 15 feet and an S4 meter at 25 feet, and sampling from R/V Langley began at station L_4 (an anchor station occupying the position of station D_5) at 1630 hrs (EST). Sampling procedures at station L_4 were similar to those at stations L_1 to L_3. Depths sampled were 5, 10, 15 and 20 feet below the water surface. Sampling at station L_4 finished at 0630 hrs (EST) on 27 August and station F' was removed at 0830 hrs (EST) the same day.

Station locations and depths sampled are shown in Table I, B.

III. RESULTS

Currents - Current measurements are expressed as two (2) minute averages of speed and direction taken at five (5) minute intervals from S4 meters and speed and direction obtained from Ruz meters once every 8 minutes 32 seconds. Results are presented as listings in Table XII, (Station F from 27 July to 12 August), Table XIII (Station F for 26-27 August) and Table XIV (station L_4 for 26-27 August) and as speed, direction and stick plots vs time in figures 12 through 14.

Tides - Tidal height variations (relative to mean sea level) with respect to time are given as hourly values in Table XV and as times and values of minimum and maximum water levels in Table XVI. Figure 15 shows water level vs. time.

C. - DISCUSSION

I. INTRODUCTION

Currents measured in the vicinity of Newport News Point during July and August 1987 were examined to determine their relationships with predicted tidal currents at Chesapeake Bay Entrance (CBE). The latter are shown in Table XVII taken from **Tidal Current Tables 1987 Atlantic Coast of North America** published annually by the US Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service. Times and strengths of minimum currents {hereafter referred to as SBF (slack water before flood) and SBE (slack water before ebb)} and maximum currents were obtained for the fifteen (15) foot level at station F' from 27 July to 11 August 1983 (Table XII-B) and all depths at remaining stations (Tables II through IX; XIII and XIV). The 15 foot level at station F' was used because of its long period of measurement, proximity to a secondary prediction station (the west end of Newport News shipping channel) and similar depth to that of predicted values (see pg 169 of 1987 tidal current tables). Examination of figures of current speed and direction (Fig 4-11 and 13-15) shows the following gross features:

1. Current speed tends to follow a truncated saw toothed or square wave pattern rather than a sine wave;
2. Once maximum flood or ebb current is reached, higher or lower "spikes" are occasionally seen but extreme values do not persist for long periods;
3. True "slack water" is rarely encountered and minimum currents greater than 10 cm/sec are not unusual; and
4. Minimum currents tend to be rotary

Because of these general features of currents in the study area, we interpret the terms "slack water" and "maximum current" in several ways:

Table XVII

1987 predicted tidal currents (slack water and maximum currents) and their times at Chesapeake Bay entrance (from NOAA Tidal Current Prediction Tables)

F-Flood, Dir. 305° True E-Ebb, Dir. 125° True

JULY

Day	Slack Water Time h.m.	Maximum Current Time h.m.	Maximum Current Vel. knots	Day	Slack Water Time h.m.	Maximum Current Time h.m.	Maximum Current Vel. knots
1	0247	0623	1.1E	16		0042	1.1F
W	0949	1156	0.5F	Th	0340	0711	1.5E
	1410	1820	1.2E		1033	1305	0.9F
	2153				1554	1934	1.5E
					2258		
2		0029	0.8F	17		0133	0.9F
Th	0321	0704	1.1E	F	0424	0806	1.4E
	1032	1245	0.6F		1130	1407	0.9F
	1504	1908	1.2E		1702	2038	1.3E
	2243						
3		0114	0.8F	18	0003	0228	0.7F
F	0358	0747	1.1E	Sa	0508	0901	1.4E
	1118	1338	0.6F		1229	1510	0.8F
	1605	2005	1.1E		1813	2145	1.2E
	2337						
4		0202	0.7F	19	0111	0328	0.5F
Sa	0438	0833	1.1E	Su	0554	1000	1.3E
	1207	1433	0.7F		1328	1619	0.8F
	1714	2106	1.1E		1925	2248	1.1E
5	0036	0255	0.6F	20	0221	0425	0.4F
Su	0522	0926	1.2E	M	0641	1054	1.3E
	1258	1532	0.8F		1425	1721	0.8F
	1827	2211	1.1E		2031	2353	1.1E
6	0137	0350	0.6F	21	0326	0526	0.4F
M	0611	1019	1.3E	Tu	0730	1149	1.3E
	1352	1634	1.0F		1519	1816	0.9F
	1941	2316	1.1E		2130		
7	0238	0447	0.6F	22		0047	1.1E
Tu	0704	1116	1.5E	W	0421	0615	0.3F
	1445	1737	1.1F		0819	1238	1.3E
	2050				1607	1907	0.9F
					2219		
8		0015	1.2E	23		0134	1.1E
W	0337	0545	0.6F	Th	0507	0702	0.4F
	0801	1212	1.6E		0906	1323	1.4E
	1539	1835	1.3F		1651	1948	1.0F
	2153				2302		
9		0113	1.3E	24		0217	1.1E
Th	0432	0644	0.7F	F	0545	0743	0.4F
	0859	1306	1.8E		0950	1406	1.4E
	1632	1932	1.5F		1731	2024	1.0F
	2251				2339		
10		0207	1.4E	25		0256	1.1E
F	0525	0739	0.8F	Sa	0619	0821	0.5F
	0957	1400	1.9E		1032	1443	1.4E
	1725	2024	1.6F		1809	2100	1.0F
	2345						
11		0300	1.5E	26	0011	0331	1.2E
Sa	0616	0832	0.9F	Su	0651	0857	0.5F
	1055	1454	2.0E		1111	1520	1.5E
	1817	2117	1.6F		1846	2131	1.0F
12	0035	0350	1.6E	27	0041	0404	1.2E
Su	0706	0927	0.9F	M	0722	0932	0.6F
	1152	1549	2.0E		1149	1555	1.4E
	1911	2209	1.6F		1922	2205	1.0F
13	0124	0440	1.6E	28	0109	0437	1.2E
M	0756	1019	1.0F	Tu	0753	1005	0.6F
	1250	1643	1.9E		1228	1630	1.4E
	2005	2259	1.5F		1959	2238	1.0F
14	0210	0528	1.6E	29	0136	0507	1.2E
Tu	0847	1113	1.0F	W	0826	1044	0.7F
	1349	1738	1.8E		1309	1709	1.4E
	2100	2347	1.3F		2038	2315	0.9F
15	0256	0619	1.6E	30	0204	0538	1.2E
W	0939	1207	1.0F	Th	0902	1125	0.7F
	1450	1836	1.7E		1354	1748	1.3E
	2158				2120	2351	0.8F
				31	0234	0613	1.2E
				F	0942	1210	0.8F
					1444	1833	1.2E
					2207		

AUGUST

Day	Slack Water Time h.m.	Maximum Current Time h.m.	Maximum Current Vel. knots	Day	Slack Water Time h.m.	Maximum Current Time h.m.	Maximum Current Vel. knots
1		0033	0.8F	16		0146	0.5F
Sa	0306	0655	1.2E	Su	0411	0820	1.3E
	1028	1259	0.8F		1150	1434	0.8F
	1541	1926	1.1E		1743	2114	1.0E
	2300						
2		0117	0.7F	17	0045	0244	0.4F
Su	0344	0740	1.2E	M	0454	0918	1.2E
	1120	1357	0.8F		1253	1540	0.7F
	1648	2027	1.0E		1855	2222	0.9E
3	0001	0212	0.6F	18	0200	0348	0.3F
M	0428	0841	1.3E	Tu	0546	1023	1.2E
	1219	1502	0.9F		1357	1648	0.7F
	1804	2143	1.0E		2004	2327	0.9E
4	0109	0313	0.5F	19		0455	*
Tu	0522	0945	1.4E	W		1121	1.2E
	1321	1609	1.0F		1455	1750	0.8F
	1923	2254	1.1E		2103		
5	0217	0419	0.5F	20		0022	1.0E
W	0626	1050	1.5E	Th	0401	0553	0.3F
	1423	1717	1.1F		0752	1215	1.3E
	2037				1546	1844	0.8F
					2152		
6		0001	1.2E	21		0109	1.1E
Th	0321	0526	0.6F	F	0442	0644	0.4F
	0737	1155	1.6E		0849	1303	1.3E
	1523	1820	1.3F		1631	1926	0.9F
	2141				2232		
7		0100	1.3E	22		0150	1.1E
F	0417	0628	0.7F	Sa	0516	0723	0.5F
	0846	1254	1.8E		0938	1344	1.4E
	1620	1920	1.5F		1710	1959	1.0F
	2237				2307		
8		0153	1.5E	23		0227	1.2E
Sa	0508	0729	0.8F	Su	0546	0800	0.6F
	0952	1351	1.9E		1021	1423	1.5E
	1714	2011	1.6F		1747	2031	1.0F
	2328				2337		
9		0242	1.6E	24		0259	1.2E
Su	0556	0821	1.0F	M	0615	0832	0.7F
	1053	1443	2.0E		1100	1458	1.5E
	1807	2101	1.6F		1823	2103	1.0F
10	0014	0329	1.7E	25	0004	0330	1.3E
M	0642	0913	1.1F	Tu	0643	0906	0.8F
	1151	1537	2.0E		1138	1532	1.5E
	1858	2150	1.5F		1858	2135	1.0F
11	0057	0415	1.7E	26	0029	0358	1.3E
Tu	0729	1004	1.2F	W	0713	0939	0.9F
	1246	1627	2.0E		1216	1605	1.5E
	1949	2236	1.4F		1933	2206	1.0F
12	0138	0502	1.7E	27	0054	0427	1.3E
W	0816	1053	1.2F	Th	0744	1015	0.9F
	1341	1718	1.8E		1256	1644	1.4E
	2041	2321	1.2F		2011	2241	0.9F
13	0217	0547	1.6E	28	0119	0456	1.3E
Th	0904	1143	1.1F	F	0819	1056	1.0F
	1436	1810	1.6E		1339	1719	1.4E
	2135				2052	2318	0.8F
14		0008	1.0F	29	0147	0531	1.3E
F	0255	0634	1.5E	Sa	0900	1138	1.0F
	0955	1236	1.0F		1429	1806	1.2E
	1533	1908	1.4E		2139	2357	0.7F
	2232						
15		0055	0.8F	30	0220	0614	1.3E
Sa	0332	0723	1.4E	Su	0948	1229	1.0F
	1050	1333	0.9F		1525	1902	1.1E
	1635	2009	1.2E		2233		
	2335						
				31		0048	0.6F
				M	0258	0703	1.3E
					1044	1330	0.9F
					1632	2009	1.0E
					2339		

Time meridian 75° W. 0000 is midnight. 1200 is noon.
* Current weak and variable.

Slack Water: that period of time when flow changed from flood to ebb (SBE) or ebb to flood (SBF) at which current speed was less than 20 cm/sec. (<u>NOTE:</u> in some instances, minimum currents were greater than 20 cm/sec and 30 cm/sec was taken as the minimum cut-off value)

1. Time of slack water could be
   a. The mid point of the period when currents were less than the minimum cut-off value,
   b. The single time when measured currents were smallest, or
   c. The time when, during periods of minimum cut-off speeds, current direction was normal to the channel (taken as 180^{o} or 360^{o})

2. The value of minimum current could be identified in two ways:
   a. The mean current during the period when speeds were less than the cut-off value and
   b. The single minimum speed during this period.

Maximum Current: As with slack water determination, maximum current times and values were associated with an extreme value initially taken as 50 cm/sec (in some cases, slower maximum currents required use of 45 or 40 cm/sec as a cut-off value)

1. The strength of maximum flood or ebb current could be taken as:
   a. The mean value of currents during the time when persistent currents were greater than the maximum cut-off value, or
   b. The absolute maximum current speed measured during any particular flood or ebb

2. Time of maximum current could be taken as:
   a. The mid-point of time when currents exceeded the cut-off value, or
   b. The time of absolute maximum current.

Because of these various interpretations of slack water and maximum current (flood or ebb), several comparisons were made between predicted tidal current features for CBE (Table XVII) and the longest time series of currents (the Fixed Reference Station - Table XII-B)

Examination of tabular and graphical presentations of current meter data shows anomalies at the begining and end of each record. These are the effects of setting and retrieving stations while meters were recording data. Additional anomalies appear in data from station D_2 (Tables IVB and IVC) resulting from data losses (for 5 minutes) due to unknown causes, and from station F' on 28 July and 11 August (Tables XII A,B and C). The 28 July anomalies resulted from movement of this station (by an unknown vessel) while those on 11 August were caused by the Coast Guard removal of this station. Segments of these records (28 to 30 July and 11 to 12 August) were not used for analysis but are left in this report for reference. All anomalies and unused data have been flagged by a vertical line in the left margin on all appropriate tables.

II. COMPARISON OF CURRENTS AT STATION F' WITH CBE PREDICTIONS

a. Speed Comparisons

Two types of speed comparisons were made: linear regressions of measured speed (both average maximum and absolute maximum of flood and ebb speeds) on predicted maxima at CBE; and the ratio of measured (average and absolute) maximum currents to predicted values. CBE current predictions and times are shown in Table XVII and flood and ebb data for station F' are shown in Table XVIII A and B respectively.

Both analyses resulted in four regression equations (each) of the form:

$$\hat{Z} = AX + B \qquad (1)$$

where $\hat{Z}$ is an estimate of the (averaged or absolute) maximum flood or ebb current at 15 ft at station F' in cm/sec and X is the tide table value of the associated current at CBE in knots. Currents ratios were obtained from

$$R = Z/X \qquad (2)$$

where R is the current ratio, Z is the measured (average or absolute) maximum current at station F' and X is as above. Values of R were found to vary with current speed and regressions of R vs. X were obtained.

These regressions were then used to estimate values of R from

$$\hat{R} = CX + D \qquad (3)$$

and 15 foot currents at stations F' were then estimated from

$$\hat{Z}' = RX = X(CX + D) \qquad (4)$$

The first type of regression analysis (eq. 1) resulted in relatively poor correlations between measured currents at station F' and those predicted for CBE (correlation coefficients, r, are in the order of 0.6 for flood and 0.4 for ebb). However, a statistical F test on both flood and ebb data set pairs showed a significant relationship at the 1% level. Regresssions using current ratios (eq. 3) had better correlation coefficients (-0.8 for flood and -0.7 for ebb). To examine the "goodness of fit" of the data to each type of regression, equations (1) and (4) were used to estimate flood and ebb values at station F' based on CBE predictions and the RMS of deviations between estimated and measured currents were determined. This statistic, in the form of standard error, shows that with the data sets used, averaged maximum flood and ebb currents have a mean deviation of 8 and 7 cm/sec from values predicted by equation (1) while use of equation (4) results in slightly higher standard errors in each case. Statistics for both methods are shown in Table XVIII-C for averaged and absolute maximum flood and ebb currents.

Table XVIII

Maximum flood currents (A) and ebb currents (B) measured at station F' (15 ft local) from 27 July to 11 August 1987. Column headings are:

a) Times when currents were greater than 50 cm/sec.
b) Average current strength during time period in (a).
c) Time of maximum current.
d) Strength of maximum current.

A - Maximum Flood

	(a)		(b)	(c)	(d)
	From	To			
Day	h m	h m	cm/sec	h m	cm/sec
27 July	19 17	22 07	58.82	19 34	71.52
28	08 47	11 04	62.41	09 30	71.52
29	Data excised due to station movement				
30					
	21 14	00 13	44.44*	23 22	52.76
31	10 02	13 27	74.38	12 10	99.65
1 Aug	22 16	01 49	59.66	00 24	76.21
	09 47	14 20	71.07	11 55	97.90
2	00 09	01 26	53.76	00 18	58.03
	11 15	15 05	66.30	13 31	87.93
3	00 54	02 11	43.30*	01 11	46.90
	12 00	15 33	76.98	14 07	100.24
4	01 56	03 13	53.34	02 21	65.07
	12 44	16 34	72.40	15 01	93.21
5	03 06	04 31	50.15	04 14	53.93
	13 55	17 28	72.21	15 29	94.96
6	03 42	05 16	56.18	04 42	62.72
	14 39	19 30	74.15	17 04	94.38
7	04 44	07 18	48.50*	05 27	59.21
	15 58	20 23	68.49	17 41	89.69
8	06 03	07 29	56.38	06 29	64.48
	17 00	20 34	74.29	18 51	90.27
9	06 22	08 56	58.77	07 05	72.69
	18 02	21 35	73.45	19 36	91.45
10	06 59	10 32	64.23	08 41	76.79
	18 47	22 46	72.97	20 55	88.52
26	19 53	22 10	51.66	21 36	58.03

* greater than 40 cm/sec

Table XVIII

B - Maximum Ebb

Day	(a) From h m	To h m	(b) cm/sec	(c) h m	(d) cm/sec
27 July	14 52	16 09	53.46	15 47	61.55
28	02 32	05 05	58.34	03 40	67.41
	15 20	18 11	53.49	15 46	59.21
29					
	Data excised due to station movement				
30					
31	03 12	07 03	58.70	05 46	71.52
	16 43	19 25	61.38	18 34	73.27
1 Aug	05 39	06 48	52.11	06 39	57.45
	17 28	20 10	53.29	19 27	60.96
2	05 50	07 50	44.43*	06 50	53.34
	19 38	21 46	53.64	20 00	60.96
3	06 18	09 09	47.12**	08 18	51.00
	18 49	21 48	52.87	21 05	62.72
4	07 46	09 54	43.31*	08 54	51.00
	19 34	23 07	64.53	21 50	86.17
5	08 47	11 47	43.81*	11 30	48.65
	22 01	00 26	56.67	23 09	69.76
6	10 32	11 32	52.83	10 58	56.28
	22 12	02 02	59.90	23 46	68.59
7	10 17	13 33	60.84	12 25	75.62
	23 05	01 22	65.59	01 05	74.45
8	11 19	14 44	66.55	13 18	81.48
	23 50	04 14	67.14	02 15	92.03
9	12 21	16 03	68.52	14 03	87.34
10	00 18	05 16	71.14	02 00	82.65
	13 14	16 13	62.96	14 39	72.10
11	02 36	05 10	58.81	04 44	68.00
26	14 37	16 45	57.63	15 46	64.48
27	02 26	06 07	64.37	04 08	79.72

* greater than 40 cm/sec
** greater than 45 cm/sec

Table XVIII

C - Statistical parameters relating predicted current strength at CBE and measured currents at station F' (15 ft).

Parameter (see text)	Flood Avg	Flood Max	Ebb Avg	Ebb Max
REGRESSION				
A	19.990	29.343	11.922	15.709
B	43.461	49.023	40.623	45.770
r	0.6387	0.5798	0.4523	0.3838
Std Error (cm/sec)	8.19	14.03	6.94	11.16

Thus, if X is the predicted current at CBE, $\hat{Z}$ is an estimate of the associated current at 15 ft at station F' and Z is the measured current at this location, then:

$$\hat{Z} = B + AX$$

r is a measure of the relationship between X and Z. A plot of X vs Z will yield a straight line when $r = \pm 1$ and will be a scatter plot when $r = 0$.

Standard error is a measure of the relationship between $\hat{Z}$ and Z. A standard error of 8 may be considered as the mean value of $|Z - \hat{Z}|$.

	Flood Avg	Flood Max	Ebb Avg	Ebb Max
RATIO				
C	-46.938	-50.426	-20.411	-23.541
D	115.633	134.565	70.676	82.716
r	-0.8255	-0.7146	-0.7400	-0.6271
Std Error (cm/sec)	8.97	13.59	7.52	11.49

Here, the ratio, R is derived from

$$R = \frac{Z}{X}$$

A regression of R against X results in

$$\hat{R} = D + CX$$

and in this case, r is a measure of the relationship between R and X. If r is less than zero, the R decreases as X increases.

In this case,

$$\hat{Z} = X\hat{R} = XD + X^2C$$

and the standard error is again related to $|Z - \hat{Z}|$.

D - Differences in time of maximum current at station F' (15 ft) and time of predicted maximum current at CBE expressed as the mean of all time differences.

	Flood		Ebb	
	Avg	Max	Avg	Max
	h m	h m	h m	h m
Difference	-1 00	-1 08	0 54	0 42
Std Error	0 28	0 48	0 27	0 34

If T_p is the predicted time of maximum current at CBE and T_f is the measured time of maximum current at station F', then

$$\text{Difference} = T_f - T_p$$

thus, using the average time when a flood current at station F' (15 ft) was over 50 cm/sec and the predicted time of maximum flood current at CBE, we find that the mean of all differences was -1 hour (i.e. on the average, maximum flood current at station F' (15 ft) was centered at a time that was one hour **before** predicted maximum flood current at CBE). A standard error of 28 minutes indicates that for this data set the variation from this average -1 hour difference in time of maximum current may be expected to have a mean value of 28 minutes.

b. **Time of Maximum Current**

Times (in Eastern Standard Time) of maximum flood and ebb current predicted at CBE were compared with measured average and absolute times (Eastern Standard Time) of these features at station F' (Table XVIII-A&B) by simply calculating time differences between the two locations, determining the average difference for each of the four conditions, applying these averages to CBE predictions and comparing the results with measured values. As with current strengths, standard errors were also determined. Results are presented in Table XVIII-D and show average maximum currents at station F' occur approximately 1 hour before predictions for CBE. Standard errors for these phase differences are on the order of half an hour.

c. **Time of Slack Water**

Comparisons of CBE predicted times of SBF and SBE (Table XVII) were made with measured times of minimum currents at station F' shown in Table XIX A and B. As with maximum current times, SBF and SBE comparisons were made using average times of minimum currents and time of absolute minimum current speeds. Additionally, comparisons were made between predicted slack water times (at CBE) and current reversal times at station F'. Procedures were the same as those used for maximum current times and results are shown in Table XIX-C.

Smallest standard error for SBF is obtained when the time of current reversal is used although there is little difference between the standard errors for all three methods of reckoning SBF (all are approximately 35 minutes). Similar standard errors were obtained for SBE time differences (31 to 39 minutes). Average time differences between minimum currents before flood and SBF predictions at CBE were on the order one hour while those for SBE were 30 to 40 minutes.

d. **Duration of Maximum and Minimum Currents**

We felt it would be useful to also examine the time intervals when currents exceeded maximum or fell below minimum cut-off values at station F'.

Table XIX

Times, strengths and comparisons of SBF and SBE (station F' and CBE) for the period 27 July - 11 August 1987.

a) Times when currents were less than 20 cm/sec
b) Average minimum currents
c) Time of absolute minimum currents
d) Strength of absolute minimum currents
e) Estimated time of current reversal

A - SBF at station F' (15 ft level)

	(a) From	To	(b)	(c)	(d)	(e)
Day	h m	h m	cm/sec	h m	cm/sec	h m
27 July	17 17	18 34	25.32**	18 09	19.93	18 04
28	05 48	06 22	18.99	06 14	17.59	06 28
	18 28	20 02	23.64**	19 36	16.41	19 06
29						
	Data excised due to station movement					
30						
	20 14	20 48	26.61**	20 48	25.21	20 31
31	08 03	08 54	33.67***	08 45	26.97	08 57
	20 16	21 25	17.00	20 25	12.90	21 28
1 Aug	08 13	09 22	21.52*	09 13	16.41	09 04
	22 01	23 01	17.44	22.35	12.31	22 40
2	09 07	10 32	14.12	09 49	9.38	09 54
	23 11	23 46	17.82	23 46	14.65	23 24
3	10 00	10 51	27.72**	10 34	25.21	10 27
	23 22	00 22	15.53	23 56	11.72	00 00
4	11 10	12 19	15.18*	11 53	12.90	11 36
5	00 15	01 07	14.74	00 50	9.97	00 58
	12 29	13 12	17.39	12 29	14.65	12 46
6	01 43	02 43	10.77	02 34	5.28	02 21
	13 40	13 48	16.12	13 40	15.83	13 31
7	03 53	04 01	19.05	03 53	18.17	03 36
	14 59	15 07	20.81*	14 59	19.93	15 02
8	04 12	04 46	13.02	04 38	9.97	04 35
	16 09	16 35	23.45*	16 35	20 52	16 04
9	05 23	05 48	29.17**	05 23	26.38	05 10
	16 54	16 54	26.97**	16 54	26.97	17 11
10	05 59	06 42	34.82***	05 59	31.65	06 19
	17 30	17 47	22.86*	17 39	22.86	17 51
26	18 28	19 10	27.06**	18 28	21.10	18 32

* less than 25 cm/sec
** less than 30 cm/sec
*** less than 35 cm/sec

Table XIX

B - SBE at station F', 15 ft (column designations same as part A of this table)

	(a)		(b)	(c)	(d)	(e)
	From	To				
Day	h m	h m	cm/sec	h m	cm/sec	h m
27 July	22 50	23 16	29.60**	23 00	28.14	23 20
28	11 30	13 03	25.65**	11 30	17.00	12 04
29	Data excised due to station movement					
30	12 59	13 59	14.07	13 25	9.97	13 38
31	00 30	02 04	34.24***	00 56	31.07	01 25
	14 27	15 01	15.12	14 43	11.72	15 00
1 Aug	02 40	03 31	11.22	02 54	3.52	03 06
	14 46	16 11	27.50**	15 03	17.59	15 06
2	02 34	04 16	9.47	03 00	4.10	03 12
	15 39	16 13	15.83	15 56	13.48	16 08
3	03 53	03 53	25.21**	03 53	25.21	04 05
	16 50	17 23	11.49	17 07	8.79	17 27
4	04 46	05 21	15.24	05 12	10.55	05 33
	17 34	17 51	15.83	17 51	12.31	18.46
5	05 39	07 31	13.02	06 14	8.79	06 22
	18 02	19 53	13.65	18 45	8.21	19 48
6	07 07	08 07	16.78	07 24	12.31	07 28
	20 12	21 03	15.16	20 25	12.90	20 41
7	08 01	09 17	14.25	08 26	10.55	08 43
	20 48	21 48	14.65	21 23	10.55	21.26
8	09 11	09 45	12.31	09 37	8.79	09 31
	22 07	22 50	15.54	22 25	12.31	22 45
9	10 30	11 12	21.89*	10 47	18.76	10 50
	22 44	23 01	29.51**	22 44	25.79	23 21
10	11 15	12 14	14.07	11 40	8.79	11 52
11	23 54	00 11	20.71**	00 03	14.07	00 15
26-27	23 35	00 52	11.90	00 01	8.21	00 13

* less than 25 cm/sec
** less than 30 cm/sec
*** less than 35 cm/sec

C - Time differences between measured slack water at station F' (15 ft) and CBE predictions.

	SBF			SBE		
	Avg Min	Abs Min	Direction Change	Avg Min	Abs Min	Direction Change
	h m	h m	h m	h m	h m	h m
Mean difference	-1 11	-1 07	-1 08	-0 40	-0 48	-0 31
Standard error	0 35	0 37	0 34	0 39	0 37	0 31

Information was extracted from Table XII-A and is presented as Table XX along with means and standard deviations of measured time intervals.

III. COMPARISON OF TUNNEL CORRIDOR DATA WITH C.B.E. PREDICTIONS

Our initial intent was to determine phase lags and speed differences between currents measured along the tunnel corridor (stations D_1 to D_3 and L_1 to L_3) and currents at station F. Because of the non-availability of data from station F while all tunnel corridor stations were sampled, our comparisons are with currents predicted for CBE. We assume standard errors developed for current parameters obtained at station F' (discussed in the previous subsection) are applicable to the nearby tunnel corridor region.

Strengths of maximum flood and ebb currents measured at the tunnel corridor stations were compared to CBE predictions. As with data from station F', comparisons were made with averaged maximum currents and absolute maximum currents using regressions (eqn 1) developed for station F'. Ratios between maximum currents and CBE predictions (as cm s^{-1}/kts) were also determined. Results of these analyses are presented in Table XXI as extracted "raw" data for flood currents (Part A) and ebb currents (Part B). Part C of Table XXI gives the differences between current speeds in parts A and B and their estimated counterparts using regression coefficients developed for currents at station F' as well as current ratios (measured/CBE predictions) expressed as cm s^{-1}/kts.

Phase lags between sampling locations along the tunnel corridor and CBE predictions for SBF, maximum flood, SBE and maximum ebb are shown in Table XXII. Duration of features is shown in Table XXIII.

Selected plots of these results are shown as isopleths of current ratios, phase lags and durations of SBF, flood, SBE and ebb in Figures 17, 18 and 19 respectively. In these figures, north is to the left and values for station L_1 (which was downstream from the tunnel corridor in the approximate relative location of the hydraulic model reference station) are

Table XX

Duration of slack water and maximum currents at 15 ft at station F' from 27 July to 11 August 1987

	SBF	Flood	SBE	Ebb
Day	h m	h m	h m	h m
27 July	1 17	2 50	0 26	1 17
28	0 34	2 17	1 33	2 33
	1 34			2 51
29				
	Data excised due to station movement			
30				
	0 34	2 59	1 00	1 51
31	0 51	3 25	1 34	3 51
	1 09		0 34	2 42
1 Aug	1 09	3 33	0 51	1 09
	1 00	4 33	1 25	2 42
2	1 25	1 17	0 05	2 51
		3 50	0 34	2 08
3	0 35	1 17	0 35	2 08
	1 09	3 50	0 17	3 33
4	1 00	1 17	0 35	2 08
	1 09	3 50	0 17	3 33
5	0 52	1 25	1 52	2 00
	0 43	3 33	1 51	
6	1 00	1 34	1 00	2 25
	0 08	4 51	0 51	1 00
7	0 08	2 34	1 16	3 50
	0 08	4 25	1 00	3 16
8	0 34	1 26	0 34	2 17
	0 26	3 34	0 43	3 25
9	0 25	2 34	0 42	4 24
	0 05	3 33	0 17	3 42
10	0 43	3 33	0 17	3 42
	0 17	3 59		2 59
11			0 17	2 34
26	0 42	2 17	1 17	2 08
27				3 41
Mean	0 45.2	2 58.2	0 50.1	2 44.3
Std. Dev.	0 25.7	1 08.4	0 31.4	0 53.8

Table XXI

A - Maximum flood currents at stations D_1-D_4 and L_1-L_4

Station	Day	Depth (ft)	(a) From h m	To h m	(b) (cm/sec)	Max Cutoff (cm/sec)	(c) h m	(d) (cm/sec)
D1	11 Jul	5	06 05	07 10	60.68	50	06 55	70.11
		14.75	06 19	08 11	59.69	50	07 02	71.70
		22	06 18	08 47	47.43	40	07 11	55.34
D2	12 Jul	14.75	06 30	09 58	72.29	60	08 16	88.64
			19 23	22 03	87.28	80	21 10	96.29
		19	06 33	10 06	61.33	50	08 20	72.40
			19 26	21 45	74.68	70	21 13	82.64
D3	13 Jul	5	08 22	10 22	75.10	70	08 47	84.87
		14.75	08 23	09 53	75.09	70	08 44	85.78
		19.2	07 36	10 42	59.05	50	08 45	73.58
D4	14 Jul	5	08 49	11 14	67.17	60	10 04	74.37
		14.75	08 45	11 34	76.17	70	09 59	84.16
		19	08 22	11 40	58.53	50	10 25	66.41
L1	11 Jul	5	06 01	08 46	48.82	40	06 37	57.43
		15	06 06	08 35	47.95	40	06 26	54.57
		25	06 32	07 34	41.88	40	07 02	43.44
L2	12 Jul	5	07 34	08 53	87.58	80	08 26	97.74
		15	07 41	08 58	87.59	70	08 09	92.45
		25	07 47	09 05	77 87.91	70	08 38	80.02
		35	07 23	09 11	76.04	70	08 16	78.56
		45	07 30	09 16	63.46	60	07 55	66.50
L3	13 Jul	5	08 13	10 56	62.09	50	08 39	68.85
		15	08 23	11 01	57.95	50	08 49	65.96
		24	08 33	10 18	54.62	50	08 59	62.13
L4	26 Aug	5	19 00	21 59	63.24	50	20 30	71.79
		10	19 05	22 05	63.29	50	20 35	69.45
		15	19 00	22 10	60.09	50	20 40	64.92
		20	19 25	21 54	55.50	50	20 55	59.76

(a) Times when current exceeded maximum cutoff
(b) Average maximum current
(c) Time of absolute maximum current
(d) Absolute maximum current

Table XXI (continued)

B - Maximum ebb currents at stations D_1-D_4 and L_1-L_4

			(a)		(b)		(c)	(d)
Station	Day	Depth (ft)	From h m	To h m	Max (cm/sec)	Cutoff (cm/sec)	h m	(cm/sec)
D1	11 Jul	5	12 00	15 45	73.52	50	14 10	86.39
		14.75	11 55	15 28	68.46	50	13 31	82.38
		22	12 31	14 55	57.38	50	13 30	66.40
D2	12 Jul	14.75	12 48	15 28	89.54	80	14 51	94.87
			01 58	04 43	92.34	80	03 28	100.23
		19	12 36	15 53	70.72	60	13 24	75.52
			02 01	04 36	76.27	70	03 16	80.93
D3	13 Jul	5	13 47	16 22	78.89	70	15 12	87.35
		14.75	13 48	16 55	78.96	70	15 29	86.67
		19.2	13 49	16 55	63.57	60	15 46	68.22
D4	14 Jul	5	02 34	05 14	84.17	80	03 09	96.02
		14.75	02 15	05 22	89.76	80	03 51	96.24
		19	02 41	04 54	72.20	70	03 45	77.26
L1	11 Jul	5	12 30	15 21	83.36	70	14 03	97.98
		15	12 03	15 26	65.70	50	14 09	76.17
		25	12 08	15 15	46.85	40	14 29	51.14
L2	12 Jul	5	14 34	15 54	90.09	80	14 34	96.88
		15	13 17	16 27	77 97.33	70	14 11	91.76
		25	13 22	16 06	80.33	70	15 39	82.88
		35	13 28	16 11	71.92	60	13 55	76.94
		45	12 46	15 50	59.68	50	12 46	76.88
L3	13 Jul	5	14 21	17 02	81.46	70	15 57	93.74
		15	14 26	16 50	66.86	60	16 18	72.06
		24	15 03	16 23	55.11	50	15 52	58.51
L4	27 Aug ~~14 Jul~~	5	01 30	04 31	77.58	60	03 00	88.66
		10	01 05	04 36	69.67	50	03 25	83.68
		15	01 10	04 10	63.97	50	03 10	70.84
		20	01 55	04 15	64.43	50	02 55	75.93

Table XXI (continued)

C - Comparison of measured and predicted currents

		Flood				Ebb			
		Diff. from regression (F') (meas-regr)		Ratios * (measured/CBE)		Diff. from regression (F') (meas-regr)		Ratios * (measured/CBE)	
Station	Depth (ft)	AVG (cm/sec)	MAX (cm/sec)	AVG	MAX	AVG (cm/sec)	MAX (cm/sec)	AVG	MAX
D1	5	-1.25	-6.15	67.422	77.900	9.06	9.03	36.760	43.195
	14.75	-2.24	-4.56	66.322	79.667	4.00	5.02	34.230	41.190
	22	-14.50	-20.92	52.700	61.489	-6.08	-10.96	28.690	33.200
D2,D4	5	3.21	-4.87	67.170	74.370	24.68	25.73	52.606	60.013
	14.75	11.25	5.49	70.347	80.943	29.40	24.47	52.861	56.743
	19	-2.49	10.39	57.783	66.168	11.92	5.26	42.718	45.543
D3	5	11.14	5.63	75.100	84.870	15.67	11.65	41.521	45.974
	14.75	11.13	6.54	75.090	85.780	15.74	10.97	41.558	45.616
	19.2	-4.91	-5.66	59.050	73.580	0.35	-7.48	33.458	35.905
L1	5	-13.11	-18.83	54.244	63.811	18.90	20.62	41.680	48.990
	15	-13.98	-21.69	53.278	60.633	1.24	-1.19	32.850	38.085
	25	-20.05	-32.82	46.533	48.267	-17.61	-26.22	23.425	25.570
L2	5	24.65	21.48	97.311	108.600	25.63	19.52	45.045	48.440
	15	25.66	16.19	97.322	102.722	32.87	14.40	48.665	45.880
	25	25.98	3.76	97.678	88.911	15.87	5.52	40.165	41.440
	35	14.11	2.30	84.489	87.289	7.46	-0.42	35.960	38.470
	45	1.53	-9.76	70.511	73.889	-4.78	-0.48	29.840	38.440
L3	5	-1.87	-10.39	62.090	68.850	18.24	18.04	42.874	49.337
	15	-6.01	-13.28	57.950	65.960	3.64	-3.64	35.189	37.926
	24	-9.34	-17.11	54.620	62.130	-8.11	-17.19	29.005	30.795
L4	5	-0.72	-7.45	63.240	71.790	21.81	22.91	59.677	68.200
	10	-0.67	-9.79	63.290	69.450	13.90	17.93	53.592	64.369
	15	-3.87	-14.32	60.090	64.920	8.20	5.09	49.208	54.492
	20	-8.46	-19.48	55.500	59.760	8.66	10.18	49.562	58.408

* Ratios are expressed as $\frac{\text{cm/sec}}{\text{knots}}$ where 1 knot = 51.4 cm/sec.

Table XXII

Phase lags (measured - CBE predictions) of maximum currents and slack water at stations D_1 - D_4 and L_1 - L_4

		SBF			Flood		SBE			Ebb	
	Depth	avg	min	dir change	avg	max	avg	min	dir change	avg	max
Station	(Ft)	h m	h m	h m	h m	h m	h m	h m	h m	h m	h m
D_1	5	-1 11	-1 12	-1 14	-1 22	-1 37	-1 25	-1 50	-1 10	-1 01	-0 44
	14.75	-1 12	-1 29	-1 32	-1 17	-1 30	-1 00	-1 13	-0 57	-1 12	-1 23
	22	-1 21	-1 30	-1 27	-0 59	-1 21	-0 45	-0 37	-0 39	-1 11	-1 24
D_2, D_4	5	-1 25	-1 23	-1 20	-1 11	-1 09	-1 16	-1 06	-1 10	-1 34	-2 19
	14.75	-1 47	-1 55	-1 46	-1 14	-1 08	-0 48	-0 46	-0 41	-1 33	-1 16
	19	-1 53	-1 52	-1 48	-1 17	-0 57	-0 35	-0 32	-1 40	-1 32	-1 51
D_3	5	-1 25	-1 18	-1 20	-0 57	-1 32	-0 08	-0 13	-0 10	-1 38	-1 31
	14.75	-1 29	-1 40	-1 31	-1 11	-1 35	-0 19	-0 01	-0 08	-1 21	-1 14
	19.4	-1 41	-1 49	-1 39	-1 10	-1 34	-0 21	-0 05	-0 13	-1 21	-0 57
L_1	5	-1 13	-1 05	-1 13	-1 08	-1 55	-0 58	-0 34	-0 42	-0 58	-0 51
	15	-1 15	-1 15	-1 24	-1 11	-2 06	-0 53	-0 45	-0 42	-1 09	-0 45
	25	-1 18	-1 10	-1 18	-1 29	-1 30	-0 55	-0 40	-0 24	-1 12	-0 25
L_2	5	-1 04	-1 04	-0 53	-1 13	-1 01	-0 46	-0 46	-0 46	-0 35	-1 15
	15	-1 38	-1 25	-1 13	-1 07	-1 18	-0 15	-0 15	+0 04	-0 57	-1 38
	25	-1 46	-1 46	-1 31	-1 01	-0 49	-0 10	-0 10	+0 08	-1 05	-0 10
	35	-1 40	-1 40	-1 26	-1 10	-1 11	-0 04	-0 04	-0 18	-0 59	-1 54
	45	-1 36	-1 36	-1 36	-1 04	-1 32	-1 12	+0 01	-0 18	-1 31	-3 03
L_3	5	-1 01	-0 52	-0 55	-0 44	-1 40	-1 12	-1 03	-4 42	-1 01	-0 46
	15	-1 13	-1 21	-1 13	-0 37	-1 30	-0 58	-0 58	-0 36	-1 05	-0 25
	24	-1 16	-1 16	-1 20	-0 53	-1 20	-0 53	-0 53	-0 31	-1 00	-0 51
L_4	5	-1 48	-2 03	-1 48	-2 11	-2 11	-0 54	-0 54	-0 39	-1 26	-1 27
	10	-1 55	-1 50	-1 43	-2 06	-2 06	-1 04	-0 49	-0 34	-1 36	-1 22
	15	-1 56	-1 44	-1 56	-2 01	-2 01	-0 59	-0 44	-0 29	-1 42	-1 17
	20	-1 50	-2 01	-1 50	-2 01	-1 46	-0 49	-0 39	-0 49	-1 22	-1 32

Table XXIII

Duration of SBF, maximum flood, SBE and maximum ebb

Station	Depth	SBF h m	MXF h m	SBE h m	MXE h m
D1	5	0 35	1 05	2 50	3 45
	14.75	0 11	2 52	0 48	3 33
	22	0 37	2 29	0 59	2 24
D2	5	0 35	2 25	0 30	2 40
	14.75	1 01	2 59	0 36	2 51
	19	0 35	3 23	0 43	2 42
D3	5	0 35	2 00	0 30	2 35
	14.75	1 04	1 30	0 48	3 07
	19.2	0 37	3 06	0 54	3 06
L1	5	0 16	2 45	1 19	2 51
	15	0 33	2 29	1 20	3 23
	25	0 49	1 02	1 03	3 07
L2	5	*	1 19	*	1 20
	15	0 26	1 17	*	3 10
	25	*	1 18	*	2 44
	35	*	1 48	*	2 43
	45	*	1 46	0 27	3 04
L3	5	0 19	2 43	0 19	2 41
	15	0 49	2 38	*	2 24
	24	1 04	1 45	*	1 20
L4	5	0 30	2 59	*	3 01
	10	0 25	3 00	0 30	3 31
	15	0 25	3 00	0 30	3 00
	20	0 22	2 29	0 20	2 20

* Insufficient data

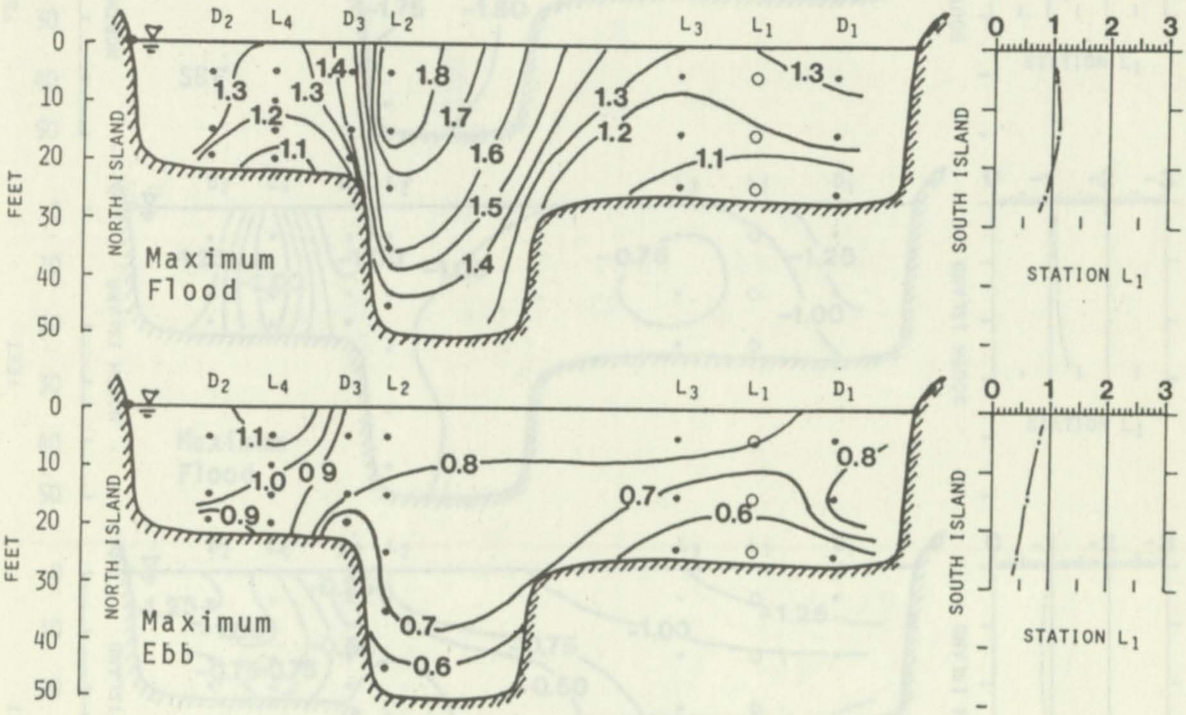

Figure 17. Ratio of averaged maximum measured currents along I664 tunnel corridor to predicted values at C.B.E.

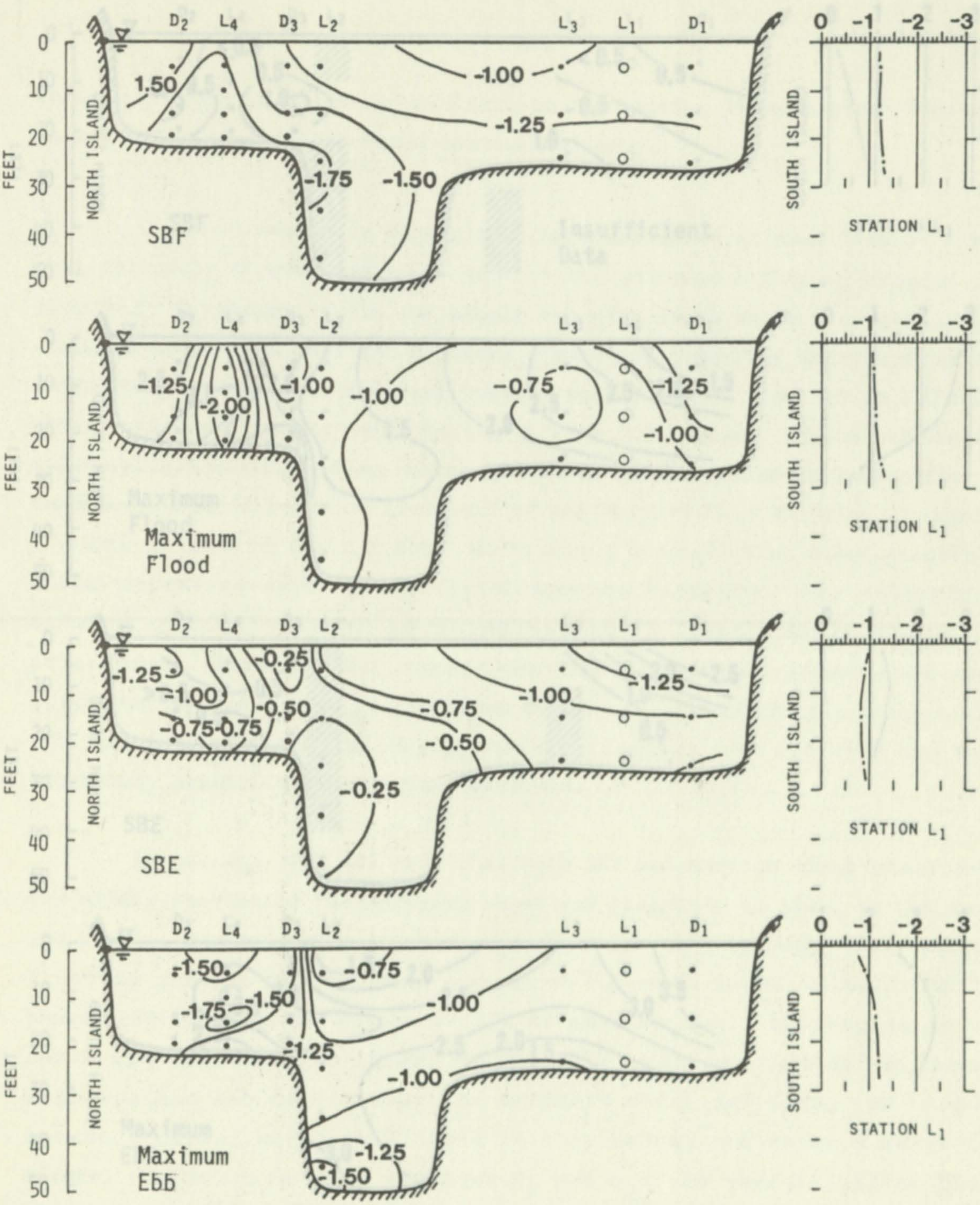

Figure 18. Phase lags of current features (in hours) along I664 tunnel corridor with reference to predicted values at CBE.

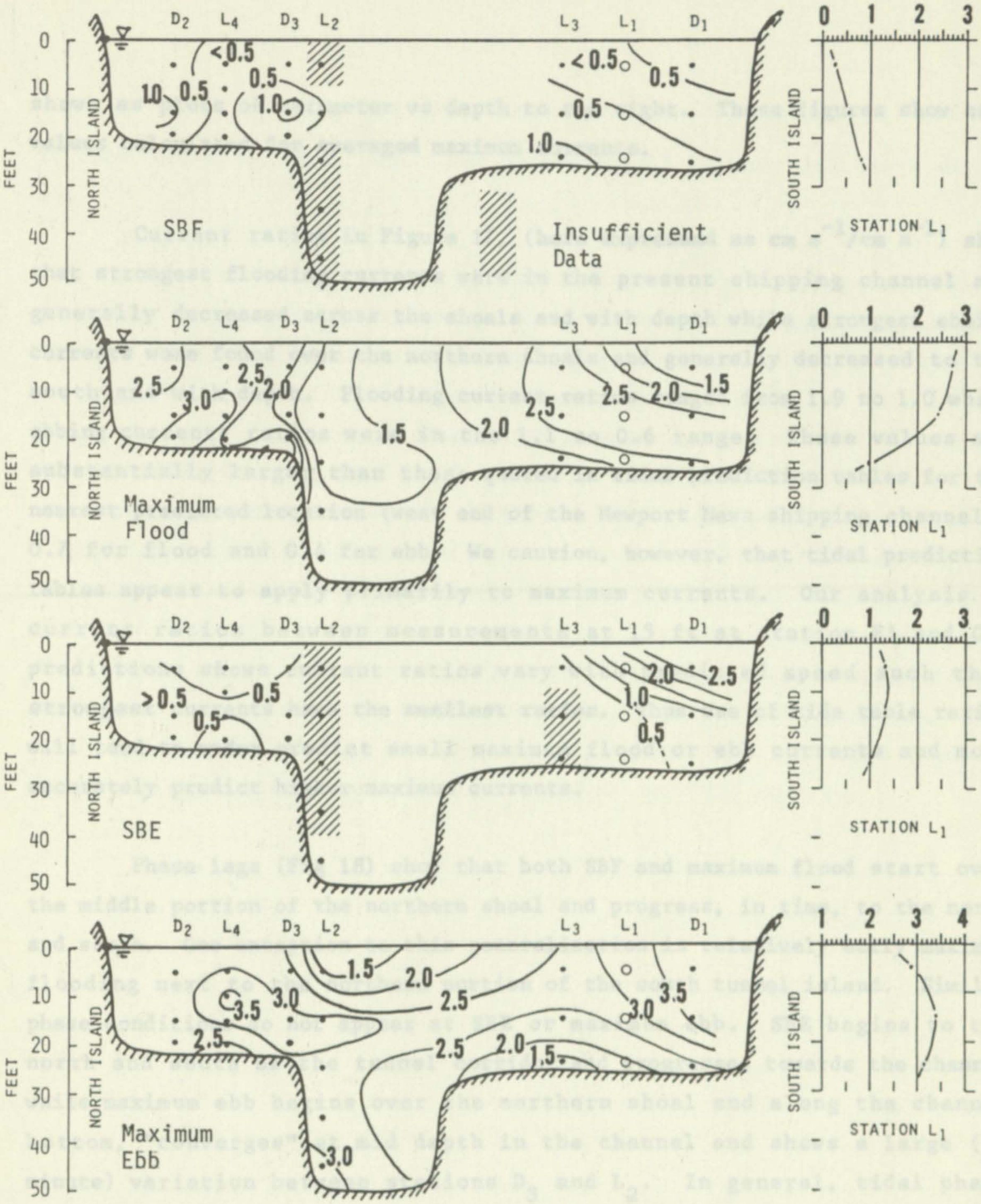

Figure 19. Duration of slack water (as minimum current less than 20 cm/sec) and maximum currents along I664 tunnel corridor.

shown as plots of parameter vs depth to the right. These figures show only values calculated for **averaged** maximum currents.

Current ratios in Figure 17, (**here expressed as cm s^{-1}/cm s^{-1}**) show that strongest flooding currents were in the present shipping channel and generally decreased across the shoals and with depth while strongest ebbing currents were found over the northern shoals and generally decreased to the south and with depth. Flooding current ratios ranged from 1.9 to 1.0 while ebbing currents ratios were in the 1.1 to 0.6 range. These values are substantially larger than those quoted in tidal prediction tables for the nearest predicted location (west end of the Newport News shipping channel): 0.7 for flood and 0.4 for ebb. We caution, however, that tidal prediction tables appear to apply primarily to maximum currents. Our analysis of current ratios between measurements at 15 ft at station F' and CBE predictions shows current ratios vary with predicted speed such that **strongest** currents have the **smallest ratios.** Thus use of tide table ratios will tend to **under predict** small maximum flood or ebb currents and more accurately predict higher maximum currents.

Phase lags (Fig 18) show that both SBF and maximum flood start over the middle portion of the northern shoal and progress, in time, to the north and south. One exception to this generalization is relatively early maximum flooding next to the northern portion of the south tunnel island. Similar phase conditions do not appear at SBE or maximum ebb. SBE begins to the north and south of the tunnel corridor and progresses towards the channel while maximum ebb begins over the northern shoal and along the channel bottom, "converges" at mid depth in the channel and shows a large (45 minute) variation between stations D_3 and L_2. In general, tidal phase variations along the tunnel corridor are from 1 hour to 1 hour and 15 minutes prior to predictions for CBE.

Duration of current features, in number of hours that minimum and maximum currents persist, are shown in Figure 19. Hatched areas in the SBF and SBE subfigures represent locations where sampling frequency was insufficient to determine starting and ending times of minimum currents. Minimum currents usually persist for 30 minutes to one hour except near the surface at Station D_1. Maximum currents persist for more than 1.5 hrs and, in some locations, (i.e. over shoal areas) extend for over 3.5 hours during ebb.

We must caution that the information presented for the tunnel corridor is based on measurements over individual **but not the same** tidal cycles and standard errors could be much greater than those developed for station F'. Additionally, we note that tidal prediction tables were prepared from information obtained **prior to** construction of the I664 tunnel islands while data reported herein was obtained **after** this construction and, we presume, reflects the effects of flow constriction due to the islands. Finally, we again point out that current speed ratios for maximum flood and ebb vary with strength of predicted current such that strong maximum currents have small ratios and weak maximum currents have large ratios. This condition is illustrated in Figure 20 which plots R for station F' vs. predicted maximum currents at CBE for maximum flood and ebb currents. Tide table values of R for 15 ft at the west end of Newport News Channel (approximate location of station L_2) are shown as solid squares.

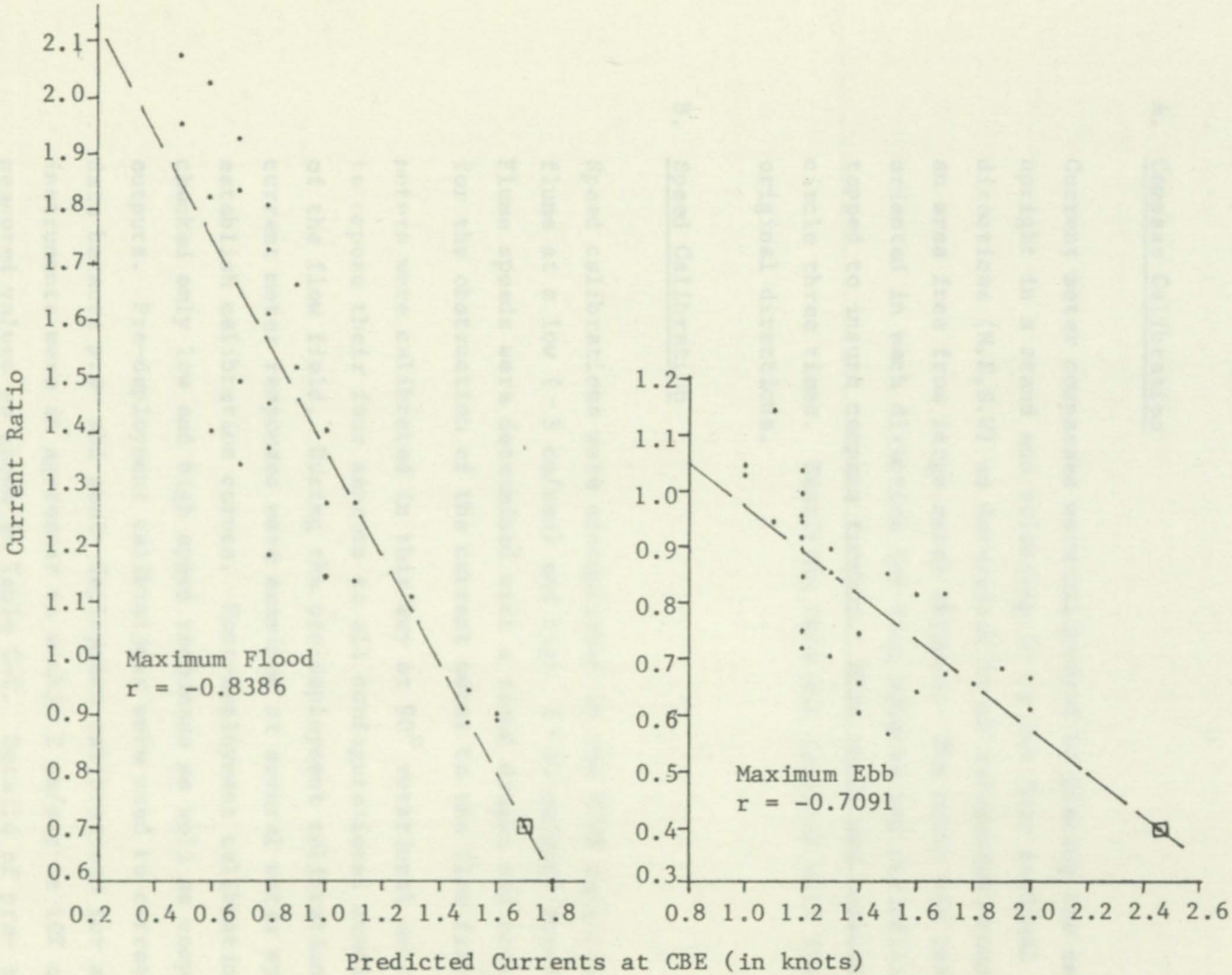

Figure 20. Current ratios at 15 ft at station F' vs. predicted currents at CBE. Boxed values from tide tables.

PART D - CURRENT METER CALIBRATIONS

All current meters used on this project were calibrated prior to and after deployment. Calibrations were of two types: compass and speed sensors. For both types of calibration, values were stored in current meter memory then dumped and analyzed.

A. Compass Calibration

Current meter compasses were calibrated by placing the meter upright in a stand and orienting it to the four cardinal directions (N,E,S.W) as determined by an independent compass in an area free from large metal objects. The meter was left oriented in each direction for five minutes and periodically tapped to insure compass freedom. Each meter was rotated full circle three times. Resulting data was compared with the original directions.

B. Speed Calibration

Speed calibrations were accomplished in the VIMS recirculating flume at a low (~ 5 cm/sec) and high (~ 80 cm/sec) speed. Flume speeds were determined with a timed drogue and corrected for the obstruction of the current meter to the flow field. S-4 meters were calibrated in this way at 90° rotational intervals to expose their four sensors to all configurational conditions of the flow field. During the pre-deployment calibrations, current meter responses were examined at several water speeds to establish calibration curves. Post-deployment calibrations checked only low and high speed responses as well as compass outputs. Pre-deployment calibrations were used to correct field data because pre- and post- deployment calibrations for all instruments were in agreement to within 2 cm/sec or 10% of measured values as shown in Table C-I. Details of pre- and post- deployment calibrations are shown in Tables C-II and C-III respectively.

The greatest shift from pre- to post-deployment calibrations was with S-4 meter 747 which shows an average post-deployment error in low speed currents of 3.94 cm/sec. The pre-deployment calibration of this meter was performed by the manufacturer who indicated the instrument performed within specifications ($\pm$ 1 cm/sec). This was taken as a zero error. Examination of the footnote on Table C-III shows low speed values of 6.72, 14.30, 7.25 and 6.25 cm/sec for water speed of 4.69 cm/sec. Disregarding the 14.30 cm/sec value and averaging the remaining three values reduces the error from -3.94 to -2.06 which, we feel, meets the requirements.

TABLE C - I

Summary of errors from current meter calibration data showing low and high speed and compass variations for pre-deployment (A), post-deployment (B) calibration runs and their differences (C).

Current meter type	ser#	Speed (cm/sec) low	Speed (cm/sec) high	Direction (degrees magnetic) 360.00	90.00	180.00	270.00
A	PRE-DEPLOYMENT						
ruz	268	1.34	-1.92	0.0	2.81	2.81	1.41
ruz	165	1.89	-3.44	8.44	8.44	4.22	----
ruz	259	1.21	-4.89	1.41	1.41	0.00	0.00
s/4	788	1.33	3.10	0.00	-6.56	-3.92	-3.27
s/4	747	0.00	0.00	0.00	0.00	0.00	0.00
s/4	786	0.00	0.00	0.00	0.00	0.00	0.00
s/4	789	0.00	0.00	0.00	0.00	0.00	0.00
B	POST-DEPLOYMENT						
ruz	268	3.01	-2.65	2.81	4.22	2.81	0.00
ruz	165	----	----	8.44	7.03	7.03	7.03
ruz	259	1.90	-1.47	2.81	2.81	4.22	2.81
s/4	788	-1.53	4.40	----	----	----	----
s/4	747	-3.94	-0.33	0.00	-3.09	1.16	4.33
s/4	786	-1.51	1.94	1.85	1.60	-2.52	-0.89
s/4	789	-1.11	0.72	1.48	3.44	-0.33	-0.62
C	DIFFERENCE						
ruz	268	-1.67	0.76	-2.81	-1.41	0.00	1.41
ruz	165	----	----	0.00	1.41	-2.81	----
ruz	259	-0.69	-3.42	-1.40	-1.40	-4.22	-2.81
s/4	788	2.86	-1.30	----	----	----	----
s/4	747	3.94	0.33	0.00	3.09	1.16	-4.33
s/4	786	1.51	-1.94	-1.85	-1.60	2.52	0.89
s/4	789	1.11	-0.72	-1.48	-3.44	0.33	0.62

TABLE C - II

Actual and measured values of speed and direction resulting from pre-deployment calibration of current meters

Current meter type	ser#		Speed (cm/sec) low	high	Direction (degrees magnetic) 360.00	90.00	180.00	270.00
ruz	268	actual	4.27	77.22				
		measured	2.93	79.14	0.0	87.19	177.19	268.59
ruz	165		4.23	78.63				
			2.34	82.07	351.56	81.56	175.78	***
ruz	259		8.83	78.35				
			7.62	83.24	358.59	88.59	180.00	270.00
S/4	788		5.41	90.57				
			4.08**	87.47**	0.00	96.56	183.92	273.27
S/4	747		0.00	0.00	0.00	0.00	0.00	0.00
S/4	786		0.00	0.00	0.00	0.00	0.00	0.00
S/4	789		0.00	0.00	0.00	0.00	0.00	0.00

*** value not taken.

**average over four:

PRE 788		747	786	789
3.84	87.34	factory	factory	factory
4.44	88.96			
4.22	88.53			
3.82	85.04			

TABLE C - III

Actual and measured values of speed and direction resulting from post-deployment calibration of current meters.

Current meter type	ser#		Speed (cm/sec) low	high	Direction (degrees magnetic) 360.00	90.00	180.00	270.00
ruz	268	actual	4.77	76.49				
		measured	1.76	79.14	357.19	85.78	177.19	270.00
ruz	165		4.72	77.24				
			***	***	351.56	82.97	172.97	262.97
ruz	259		4.83	76.49				
			2.93	77.96	357.19	87.19	175.78	267.19
S/4	788		5.07	84.86	360.00	90.00	180.00	270.00
			6.60**	80.46**	***	***	***	***
S/4	747		4.69	84.33				
			8.63**	84.66**	0.00	93.09	178.84	265.67
S/4	786		5.12	83.30				
			6.63**	81.36**	358.15	88.40	182.52	270.89
S/4	789		5.09	83.68				
			6.20**	82.96**	358.52	86.56	180.33	270.62

*** value not taken.

**average over four:

POST	788		747		786		789	
	7.62	79.42	6.72	83.19	5.80	83.05	8.04	82.63
	5.94	80.60	14.30	83.56	4.62	81.95	5.94	80.21
	6.90	81.80	7.25	85.15	7.18	79.77	5.80	85.57
	5.95	80.00	6.25	86.75	8.93	80.68	5.00	83.43